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DRAG OF HEATED CIRCULAR CYLINDERS
a report to the
Energy Research and Development Administration
by
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DRAG OF HEATED CIRCULAR CYLINDERS

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ABSTRACT

A stainless steel circular cylinder shape is heated to temperatures exceeding 1500°F and wind tunnel tested to obtain drag data. The results are presented as C_D vs. model surface temperature with parameters Re_∞ , α , and surface roughness. On comparison with unheated C_D vs. Re_∞ plots, a similar, but reverse, turbulent-laminar transition is seen to occur, induced by increasing surface temperature. Verification with C_p vs. θ plots shows that the high temperature cylinder behaves exactly like the laminar room temperature cylinder (even for normally turbulent freestream Re). This temperature induced reverse transition is explained in terms of a "reference Reynolds number" Re^* which is calculated using Eckert's boundary layer reference temperature in place of the freestream temperature. It is found that plots of C_D vs. Re^* for heated cylinders are comparable to normal C_D vs. Re curves for unheated models and that Re^* can be used to effectively determine the drag behavior and pressure distribution of heated cylinders.

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NOMENCLATURE

C_D	Coefficient of drag, $\frac{D}{\frac{1}{2} \rho_{\infty} V_{\infty}^2 S}$
C_p	Pressure coefficient, Eq. 7
D	Drag force on cylinder
L	Characteristic length equal to model cylinder diameter, 7.36 inches
P	Pressure at a point on the model surface
P_{∞}	Freestream static air pressure
R	Gas constant
Re_{∞}	Freestream Reynolds Number, $\frac{\rho_{\infty} V_{\infty} L}{\mu_{\infty}}$
Re^*	Boundary layer reference Reynolds Number, $\frac{\rho^* V_{\infty}^* L}{\mu}$
S	Frontal area of cylinder, $16.53 \times 7.36 \text{ in}^2$
T_{∞}	Freestream temperature
T_w	Surface temperature of the heated model cylinder
T^*	Eckert reference temperature, Eq. 3
V_{∞}	Freestream velocity
α	Angle, measured from the vertical, of the cylinder axis tilted into the flow, Fig. 4
θ	Circumferential angle on cylinder, Fig. 26
ρ_{∞}	$= \frac{P_{\infty}}{RT_{\infty}}$
ρ^*	$= \frac{P_{\infty}}{RT^*}$
μ_{∞}	Freestream viscosity of air as given by Sutherland's Law, Eq. 2
μ^*	Viscosity evaluated at T^*

INTRODUCTION

The Energy Research and Development Administration (ERDA) has been conducting drop tests from high altitude of a heated cylinder in order to obtain aerodynamic data for use in their satellite power supply program. The cylindrical heat source for the Multi-Hundred Watt Radio-isotope Thermoelectric Generator (MHW-RTG), shown in Figure 1, is to be launched into synchronous earth orbit. Inside this cylinder are many fuel sphere assemblies containing radioisotope fuel material which generates much heat used in the production of electric power. What ERDA wants to know is how this heat will affect the drag characteristics and hence the terminal velocity of the re-entering cylinder, so that proper design will prevent rupture of the cylinder upon ground impact. Since drop testing is an expensive and difficult way of testing, ERDA sought other means of gathering this data. The Aerospace and Ocean Engineering Department at Virginia Polytechnic Institute and State University undertook the job of wind tunnel testing a right circular cylinder shape for the purpose of investigating the changes of drag and pressure with surface heat at various freestream Reynolds numbers, angles of attack, and surface roughnesses.

There have been many investigations of the change in drag with Reynolds number on a right circular cylinder at room temperature and various surface roughnesses.^{1,2,3} A sudden decrease in drag coefficient at low Reynolds number marks a boundary layer transition from laminar to turbulent flow (Fig. 2 from Ref. 4). This transition is also observed on spheres and, for low freestream turbulence, always occurs at a Reynolds number of 3.85×10^5 . Such well behaved transition is

not to be found with cylinders, however. Repeated tests in the transition regime will not necessarily produce a specific Reynolds number for boundary layer transition. The C_D drop which marks transition can thus occur anywhere within a small range of Reynolds number for a circular cylinder.

The effect of a heated surface on boundary layers and in flat plate aerodynamics has also been extensively studied.^{5,6,7,8} Yet, surprisingly little has been done to investigate the effects of surface temperature on the flow around circular cylinders. Since surface heating would influence the characteristics of the boundary layer, it should also affect the drag and behavior of the boundary layer transition. With this in mind, an original investigation of C_D behavior of a circular cylinder with varying surface temperature was undertaken.

DESCRIPTION OF EXPERIMENT

Tests were conducted in the VPI Subsonic Stability Tunnel (Fig. 3). This is a continuous circuit tunnel and features a very low turbulence factor. The closed test section is 28 feet long, and is 6 x 6 feet square. The walls in the test section can be curved in order to produce the flow encountered in turning flight.

The circular cylinder shape which ERDA wanted VPI to test is shown in Figure 4. The room temperature data obtained with this model was compared with data in the literature on an unmodified right circular cylinder, with the conclusion that the small indentation on the top of the model cylinder would have no effect on the results obtained for this study.

Because of the high temperatures involved, a strain gauge balance system could not be used. Instead, force data was obtained using the stability tunnel's six-component mechanical balance system, and displayed on the digital printer which reads directly in engineering units (pounds, foot-pounds). The entire tunnel and balance system was built at NASA Langley and used there for many years before acquisition by VPI. Since then, the tunnel and its circuitry have been continuously modernized and are in very good condition. The reliability and accuracy of data from the tunnel is excellent.

The room temperature or "cold" C_D vs. Re_∞ data were first obtained with the smooth cylinder for Reynolds number up to and slightly exceeding 10^6 , for angles of attack (cylinder axis measured from the vertical, Fig. 4) 0° , 15° , 30° and 45° . The model was then heated to a surface temperature (T_W) exceeding 1500°F , and C_D vs. T_W obtained for many different fixed Re_∞ at angles of attack 0° , 15° , 30° and 45° . The model was then knurled, using a standard diamond knurl, to roughnesses of 2.5, 5, and 10 mils, with the procedure of the smooth cylinder repeated for each roughness.

The model was machined from 304 stainless steel. This material permitted repeated heating to a cherry-red 1600°F with minimal corrosion and no flaking. The model was heated using a circular array of six infrared propane gas industrial process burners which were lowered around the model through a trap door installed in the test section ceiling. Surface temperatures were measured from 16 chromel-alumel thermocouples, located around the model as shown in Fig. 5. The thermocouples, insulated to withstand temperatures of 1800°F , were placed

as near the model surface as possible by driving a tapered stainless steel plug into a hole fixing the thermocouple wires as shown in Figure 6. The lines ran out the bottom of the model at the tunnel mounting point, and were connected to strip chart recorders, giving a continuous temperature readout.

The testing format called for freestream Reynolds numbers up to 10^6 . At maximum tunnel power, the 6 x 6 foot test section attains a maximum Reynolds number for this model of 9×10^5 . In order to achieve the extra speed necessary for a freestream Reynolds number of 10^6 , one wall was curved in, reducing the size of the test section in the vicinity of the model to 4 x 6 feet, Figure 7.

Tunnel speed was measured using a pitot tube placed in line with the model. This allowed accurate determination of speed with minimal blockage influence on the readings. To assure that the change in test section size did not introduce blockage effects, tests were run at overlapping ranges of speed in both section configurations and it was observed that the data merged to a single curve.

When the maximum surface temperature was obtained by the model (somewhere over 1600°F), the burners were retracted through the ceiling by a pulley system, and the tunnel was simultaneously brought up to the desired speed. The model would also be tilted into the flow at this time if desired. When the speed was obtained and the mechanical balance stabilized, a force reading would be taken on the printer readout system, and a mark made on the strip chart to indicate the temperature at the time of the reading.

The sixteen thermocouples were connected to a six-channel readout. One channel could be switched to read all remaining thermocouples. During preliminary tests, six thermocouples strategically located around the model were found to satisfactorily describe the surface temperature of the model. These temperatures were found to be quite close to each other, and thus a uniform temperature was found to exist all around the model. This was due to a good soak temperature being achieved by the stainless steel model.

Initial data was taken every 30 seconds, then at 1 minute intervals as the rate of cooling decreased. The readings were taken, in the majority of cases, until the model cooled to near freestream values.

Data was reduced as C_D vs. Re_∞ (at fixed α and roughness) for the cold runs, and as C_D vs. T_W (at fixed Re_∞ , α , and roughness) for the hot runs.

DATA AND RESULTS

For the unheated smooth cylinder, the variation in drag coefficient with Reynolds number that was obtained at zero angle of attack is presented in Figure 8. This curve is seen to be similar to previously published cylinder data with laminar-turbulent transition at Reynolds numbers between 3 and 5 times 10^5 .

The effect of tilting the model into the flow is shown in Figure 9. A delayed and less pronounced transition is seen to occur for increasing α , and a general flattening of the curve results. At 45° , C_D becomes virtually constant.

Figures 10 and 11 show the influence roughness effects have. In Figure 10, a 2.5 mil crest-to-trough surface roughness is compared with the smooth cylinder for zero α . One observes a slightly higher laminar and turbulent drag coefficient with the rough surface, due to increased skin friction. Transition occurs within the normal Reynolds number region. However, this region occurs at lower Re_∞ as roughness effects become more significant and cause the boundary layer to become turbulent more easily (Figure 11). A more pronounced increase in the turbulent and laminar values of C_D is also observed.

With these cold data available for reference and comparisons, the effects produced by heating the cylinder can now be investigated. The model is heated to more than 1500⁰F and exposed to a constant speed flow. Taking a look first at the smooth case at zero α and a nominal Re_∞ of 8×10^5 (Figure 12), it is seen that as the temperature of the model increases to some value above room temperature, the drag coefficient enters a transition region where it changes from a low to a higher value. This looks like a cold C_D vs. Re_∞ curve in reverse! It is observed that the low C_D value for the heated case is very nearly the value for the cold turbulent C_D , while the high C_D value approaches the cold laminar value.

Now the angle of attack of the heated cylinder is varied. Figure 13 presents the results of increasing α at the same nominal Reynolds number (velocity) for the smooth cylinder. The transition region diffuses as the curve flattens out. C_D is nearly constant at $\alpha = 45^0$. An interesting comparison can be made with Figure 9. For each α , the high and low values of C_D are quite close.

To illustrate the effect of roughness Figures 14, 15, and 16 show the results for $Re_\infty = 10^6$ and $\alpha = 0$ as a sample case. Figure 14 shows a smooth cylinder plot. Note again how the high and low C_D values approach the laminar and turbulent values, respectively, of the cold cylinder. The transition also occurs within a narrow range of model surface temperature. Figure 15, for the 2.5 mil roughness, shows a transition occurring at higher T_W . The high and low C_D increase slightly, due to skin friction just as in the cold case. Figure 16 shows a continuation of these trends with increasing roughness. It is noteworthy to compare with the cold cases, Figure 11. Similar effects were noted at other α and Re_∞ values.

So far, a comparison has been made of C_D variations between hot and cold runs for the parameters α and roughness. The C_D vs. T_W data look like the reverse of the C_D vs. Re_∞ plots. It appears that at high T_W , the C_D behaves as if the boundary layer were laminar. As T_W is lowered, the C_D seems to transition to a turbulent boundary layer behavior. Thus it appears that as T_W increases, the boundary layer takes on the characteristics of a decreasing Reynolds number, a sort of reverse transition. This would account for the direction of shift of the C_D transition region due to roughness observed for both the hot and cold data of Figures 16 and 11. The trend is for transition occurring at lowering effective Reynolds number with increasing roughness.

One can further experimentally check this temperature effect on boundary layer transition by observing the effects of different Re_∞

on the C_D vs. T_W plots. Figure 17 shows the trend for the smooth cylinder at zero angle of attack, and Figure 18 is the trend for a 5 mil surface at zero angle. In both cases, the suspected transition in the boundary layer from turbulent to laminar flow occurs at increasing T_W for increasing Re_∞ , and this is how it should be if what is being observed is a temperature-induced reverse transition. As T_W increases (boundary layer observed to behave more laminar) the free-stream velocity (and hence Re_∞) must increase to make the flow more turbulent in order for the boundary layer to remain in the transition region, and this is the effect observed in Figure 17 and 18.

A reverse transition seems to be occurring. It is well known that boundary layer transition is a function of Reynolds number. Ordinarily for an unheated body, we find transition depends on free-stream Reynolds number, Figure 2. Reynolds number is normally defined as

$$Re_\infty = \frac{\rho_\infty V_\infty L}{\mu_\infty}, \quad (1)$$

where $\rho_\infty = \frac{P_\infty}{RT_\infty}$ and μ_∞ is a function of temperature, given by Suther-

land's Law as

$$\mu_\infty = \frac{2.27 T_\infty^{3/2}}{(T_\infty + 198.6)} \times 10^{-8} \frac{\text{lb-sec}}{\text{ft}^2}. \quad (2)$$

Thus $Re_\infty = f(P_\infty, T_\infty, V_\infty, L)$. However, since transition is occurring in the boundary layer, it seems reasonable to use a boundary layer temperature, some value between the surface and freestream temperatures.

The well-known Eckert's reference temperature for boundary layers⁹ is used as an initial trial value for temperature,

$$T^* = T_{\infty} + 0.5(T_W - T_{\infty}) + 0.22 (T_{aw} - T_{\infty}), \quad (3)$$

but since $T_{aw} \approx T_{\infty}$,

$$T^* = \frac{T_W + T_{\infty}}{2}, \quad (4)$$

so the boundary layer reference temperature in this case is the average of the surface and freestream temperatures. Thus for a heated cylinder, it makes more sense to make calculations based on a "reference"

Reynolds number,

$$Re^* = \frac{\rho^* V_{\infty} L}{\mu^*}, \text{ where } \rho^* = \rho(T^*) \text{ and } \mu^* = \mu(T^*). \quad (5)$$

Thus $Re^* = f(P_{\infty}, T^*, V_{\infty}, L)$. (6)

During a test run at constant speed, the temperature of the model changes with time. Thus the boundary layer reference Reynolds number, Re^* , changes during a given run. To see if the observed C_D transition is a function of Re^* , a plot of C_D vs. Re^* can be constructed from any hot run desired and compared with the corresponding cold C_D vs. Re_{∞} curve. For example, Figure 19 shows a C_D vs. Re^* plot for the 5 mil heated cylinder at zero α . This curve looks like an ordinary cold C_D vs. Re_{∞} curve at $\alpha = 0^0$, and yet note that this curve is produced at constant freestream Reynolds number. It is Re^* which is changing, because the decreasing model temperature is causing T^* to change.

The laminar C_D values are obtained when the model is hot, and become turbulent as the model cools. Figure 20 shows that by superposing the 5 mil curve from Figure 11 onto Figure 19, a comparison is made between cold Re_∞ and hot Re^* values for the same cylinder finish and α . By using data from other hot runs, these comparisons can be made for other values of α , roughness, and Re_∞ . The results are presented in Figures 21-24.

Transition from laminar to turbulent flow causes more than just a C_D change. The pressures at various points on the model surface also change, as shown by comparing available plots from the literature of pressure coefficient vs. circumferential angle, or C_p vs. θ , at various Re_∞ (Fig. 25 from Ref.10). Pressure coefficient is a non-dimensional measure of pressure at a point, and is defined as

$$C_p \equiv \frac{P - P_\infty}{\frac{1}{2} \rho_\infty V_\infty^2} \quad (7)$$

The circumferential angle θ is measured clockwise from the line parallel to the freestream flow, Figure 26. In order to obtain the necessary pressure data, the model was drilled and fitted with 13 pressure tops spaced every 15° on one side of the model, Figure 27. The pressure lines were connected to a water manometer board. A typical cold cylinder plot is shown in Figure 28 for laminar Re_∞ of 2.60×10^5 , and a turbulent Re_∞ of 6.33×10^5 is shown in Figure 29. Both compare well with published data. It is noted that the separation moves aft as Re_∞ increases and the flow becomes turbulent. Figure 30 shows the progression of C_p vs. θ curves for increasing Re_∞ . It is

seen that transition to turbulent flow causes a more complete pressure recovery which reduces the pressure drag on the cylinder.

The cold data now establishes a basis on which to compare hot data. Since, during a heated run, the surface pressures would change rapidly and continuously, it was necessary to take pictures of the manometer board and note the thermocouple readings at that instant. Figure 31 shows, for a freestream Re_∞ of 8.90×10^5 , the C_p vs. θ curve when T_w was at 1061°F . The computed value of Re^* is 265,075. In order to compare this with Figure 28 (the cold C_p vs. θ curve at $Re_\infty = 260,515$), the two are plotted together in Figure 32. The curves nearly coincide. Figures 33 and 34 show transitional and turbulent Re^* comparisons with similar freestream Re .

There is no question that at high surface temperatures (low Re^*) a reverse transition to laminar flow has occurred. The reference Reynolds number seems to be accurate for determination of laminar or turbulent properties.

CONCLUSIONS

It is seen that increasing the model surface temperature affects the behavior of the boundary layer. A reference Reynolds number, Re^* , can be calculated using Eckert's boundary layer reference temperature. As T_w increases, Re^* decreases and can result in laminar boundary layer values even though freestream Re may be quite turbulent. The Re^* values accurately determine the C_D characteristics of the cylinder. Thus, in order to find C_D for a heated circular cylinder at any

temperature, one can calculate an Re^* , then use that value on a cold C_D vs. Re_∞ curve for the same surface finish and angle of attack.

The results obtained during the wind tunnel tests were accurate and consistent. This demonstrates the effectiveness and utility of this method of testing over aircraft drop tests. Tunnel testing is easier, more repeatable, and much less expensive than other testing methods.

REFERENCES

1. Achenbach, E., "Distribution of Local Pressure and Skin Friction Around a Circular Cylinder in Cross Flow up to $Re = 5 \times 10^6$," *Journal of Fluid Mechanics*, Vol. 34, pp. 625-639, 1968.
2. Roshko, A., "Experiments on the Flow Past a Circular Cylinder at Very High Reynolds Number," *Journal of Fluid Mechanics*, Vol. 10, pp. 345-361, 1961.
3. Achenbach, E., "Influence of Surface Roughness in the Cross Flow Around a Circular Cylinder," *Journal of Fluid Mechanics*, Vol. 46, pp. 321-335, 1971.
4. Schlichting, H., Boundary Layer Theory, 4th Edition, McGraw-Hill, New York, 1960, p. 16.
5. Bloom, M., "The Effect of Surface Cooling on Laminar Boundary Layer Stability," *Journal of Aeronautical Sciences*, Sept. 1951, pp. 635-636.
6. Libby, P. A. and Morduchow, M., "Method for Calculation of Compressible Laminar Boundary Layer with Axial Pressure Gradient and Heat Transfer," NACA TN 3157, 1954.
7. Morduchow, M. and Grape, R. G., "Separation, Stability and Other Properties of Compressible Laminar Boundary Layer with Pressure Gradient and Heat Transfer," NACA TN 3296, 1955.
8. Blohm, R. W., III, and Marchman, J. F., III, "Heat Transfer Effect on a Delta Wing in Subsonic Flow," *Proceedings of the 1974 Heat Transfer and Fluid Mechanics Institute*, Stanford Press 1974, pp. 220-227.
9. Holman, J. P., Heat Transfer, 3rd Edition, McGraw-Hill, New York, 1972, p. 163.
10. Schlichting, H., Boundary Layer Theory, 4th Edition, McGraw-Hill, New York, 1960, p. 19.

FIGURES

FIGURE 1. MHW-RTG HEAT SOURCE

FIGURE 2. NATURE OF TRANSITION ON RIGHT CIRCULAR CYLINDER

FIGURE 3. CUTAWAY VIEW OF STABILITY WIND TUNNEL

FIGURE 4. STAINLESS STEEL MODEL CYLINDER

FIGURE 5. LOCATIONS OF THERMOCOUPLES

FIGURE 6. METHOD OF THERMOCOUPLE MOUNTING

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FIGURE 8 . COLD C_D VS. Re_∞ FOR SMOOTH CYLINDER AT $\alpha = 0^\circ$

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FIGURE 11. EFFECTS OF INCREASING SURFACE ROUGHNESS ON COLD C_D VS. Re_∞

FIGURE 12. CHANGE IN C_D WITH SURFACE TEMPERATURE AT $Re_\infty = 8.0 \times 10^5$

FIGURE 13. EFFECTS OF α ON HOT C_D VS. T_W WITH SMOOTH CYLINDER AT $Re_\infty \approx 8 \times 10^5$

FIGURE 14. CHANGE IN C_D WITH SURFACE TEMPERATURE AT $Re_\infty = 1.06 \times 10^6$

FIGURE 15. BEGINNING OF SURFACE ROUGHNESS EFFECTS ON HOT C_D VS. T_W AT $\alpha = 0^\circ$

FIGURE 16. EFFECTS OF INCREASING SURFACE ROUGHNESS ON HOT C_D VS. T_W FOR $\alpha = 0^\circ$ at $Re_\infty \approx 10^6$

FIGURE 17. EFFECTS OF Re_∞ ON SMOOTH FINISH C_D VS. T_W AT $\alpha = 0^\circ$

FIGURE 18. EFFECTS OF Re_∞ on 5 MIL FINISH C_D VS. T_W AT $\alpha = 0^\circ$

FIGURE 19. HOT C_D VS. Re^* AT $Re_\infty = 1.06 \times 10^6$

FIGURE 20. COMPARISON OF Re_∞ AND Re^* FOR DETERMINING TRANSITION, 5 MIL, $\alpha = 0^\circ$

FIGURE 21. COMPARISON OF Re_∞ AND Re^* FOR DETERMINING TRANSITION, 10 MIL, $\alpha = 0^\circ$

FIGURE 22. COMPARISON OF Re_∞ AND Re^* FOR DETERMINING TRANSITION, SMOOTH, $\alpha = 0^\circ$

FIGURE 23. COMPARISON OF Re_{∞} AND Re^* FOR DETERMINING TRANSITION, SMOOTH, $\alpha = 15^\circ$

FIGURE 24. COMPARISON OF Re_∞ AND Re^* FOR DETERMINING TRANSITION, SMOOTH, $\alpha = 45^\circ$

FIGURE 25. LAMINAR AND TURBULENT PRESSURE VARIATIONS WITH CIRCUMFERENTIAL ANGLE

FIGURE 26. DEFINITION OF θ

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FIGURE 29. TURBULENT PRESSURE DISTRIBUTION ON COLD SMOOTH CYLINDER

FIGURE 30. EFFECT OF Re_{∞} ON SMOOTH SURFACE COLD C_p VS. θ CURVES

FIGURE 31. HOT C_p VS. θ AT $Re_\infty = 8.9 \times 10^5$ and $T_W = 1001^\circ F$

FIGURE 32. COMPARISON OF HOT AND COLD C_p VS. θ AT LAMINAR VALUES $Re^* \sim Re_\infty$

FIGURE 33. COMPARISON OF HOT AND COLD C_p VS. θ AT TRANSITIONAL VALUES $Re^* \approx Re_\infty$

FIGURE 34. COMPARISON OF HOT AND COLD C_p VS. θ AT TURBULENT VALUES $Re^* \approx Re_\infty$